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EVALUATION OF 2-D TRANSVERSE BEAM PROFILE MONITOR USING GAS SHEET AT J-PARC LINAC*

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Abstract

A transverse beam profile monitor, which detects ions or luminescence generated by the interaction between the beam and the gas molecules distributed in a sheet shape, has been developed in the J-PARC LINAC. To know about the gas density distribution of the sheet-shaped gas, which affects the intensity distribution of the detected signal, the calculation by the Monte Carlo simulation code was performed. The calculation results showed that the gas with a narrow width along beam direction distributes enough uniformly within a realistic beam cross-sectional size. In addition, the unsaturated region against the MCP voltage and the injected gas pressure are evaluated based on the measurement with a beam. The results showed that the measurement in the low injected gas pressure with the appropriate applied voltage range is important to measure the beam profile in the unsaturated region.

INTRODUCTION

A gas-sheet based beam profile monitor, a gas-sheet monitor, has been developed to measure the transverse beam profile [1-3]. Because the intensity of the ions or fluorescence, which are generated by the interaction between the gas molecules and the beam, is proportional to the beam intensity, their intensity distribution has the information about the beam profile. In the monitor, the unwanted influence on the beam, such as a scattering or charge exchange, will be negligible due to the rarefied gas density and thin thickness of the sheet-shaped gas, which is around 10^7-10^8 molecules/mm^3 and less than a few mm, respectively. Thus, the gas-sheet monitor is a candidate of a non-destructive beam profile monitor, especially for high-intensity beam accelerators to prevent unallowable levels of radiation. So far, the gas-sheet generator had been developed to obtain the uniform and thin sheet-shaped gas distribution [1, 2]. As confirmation experiments, the transverse beam profiles of the electron and proton beam with the energy of 30 keV and 10 MeV, respectively, were observed [2]. In response to the successful results, the gas-sheet monitor system was installed to the J-PARC LINAC, which accelerates H- beam to 400 MeV [3]. The conceptional diagram of the monitor is shown in Fig. 1. The sheet-shaped nitrogen gas is generated in the beam trajectory at an angle of 30° by passing through the 2 slits of the gas-sheet generator. The slits are located both up and bottom directions at the prospect of more uniform gas distribution than with the prototype gas-sheet generator which has an only one-sided slit. The gas is provided to the slits through the gas injection line with a gas reservoir. Although the system was designed for both ion and fluorescence detection, we have performed ion detection so far because the ionization cross section is much larger than the fluorescence one. The spatial resolution in the ion detection will be about 0.1 mm, which is decided by the resolution of the microchannel plate (MCP). The dynamic range of 10^3 is expected to be obtained by changing the applied voltages on the MCP. They will be measured by using the beam in the near future.

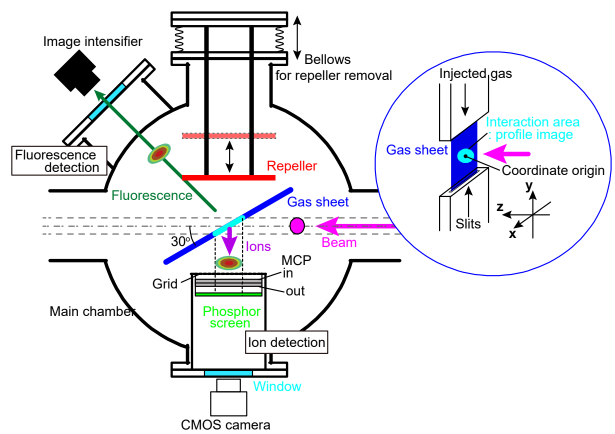

Figure 1: Conceptional diagram of a gas-sheet based beam profile monitor in J-PARC LINAC.

Several factors are related to whether this monitor can observe the beam profile properly. The density uniformity of the sheet-shaped gas in the beam cross-sectional area is one of such factors because the intensity distribution of the detected signal is proportional to the gas density. Further, the applied voltage on the MCP and the pressure in the gas injection line are other factors for the proper beam profile measurement because too large voltage or pressure would make the profile peak saturated. Thus, the purpose of this article is to evaluate the gas-sheet monitor in J-PARC LINAC from the perspective of the uniformity of the gas density distribution and the dependence of the beam profile on the MCP voltage and the gas injection line pressure. First, the uniformity of the gas density is evaluated three-dimensionally with the Monte Carlo simulation. Secondly, the unsaturated region against the MCP voltage and the gas injection line pressure are evaluated based on the measurement.

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UNIFORMITY OF THE GAS DENSITY DISTRIBUTION

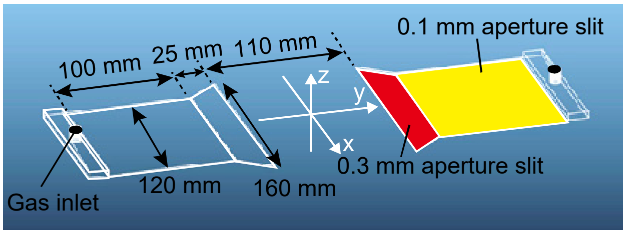

Figure 2: Geometrical of the slit model for the gas density distribution calculation. The z-axis is the beam direction, while the x- and y-axis is a horizontal and vertical axis, respectively, in the real space.

The gas density distribution had been calculated for the slits with several basic shapes [4]. It was concluded that the slit, which has a long flow path relative to the slit width, can generate the thin gas sheet. Figure 2 shows the slits model for the system in the J-PARC LINAC. Two slits are set facing each other at 110 mm distance. The depth of the flow path is 100 mm with the slit aperture size of 0.1 mm × 120 mm. Subsequently, the aperture size becomes wider to 0.3 mm × 160 mm near the gas outlet and a differential pumping port is put in this region in the actual gas-sheet generator. This wider aperture region has both roles as the secondary slit to cut a diffuse part of gas molecules from the first slit and as a pump for the useless gas molecules, which is cut by the secondary slit. Experimentally, the pressure in the main chamber became one tenth when the differential pump was switched on comparing with the off case. Thus, roughly 90 % of the gas molecules passing through the first slit are differentially pumped out and the remaining 10 % contribute to generating the gas sheet. In the gas distribution calculation, the differential pumping is not modeled for the sake of simplicity. Thus, the calculated pressure shown later is about ten times larger than the actual one. However, it is enough to discuss the relative uniformity of the gas density distribution.

The calculation was performed by the Monte Carlo simulation code Molflow+ [4]. In the code, the interaction between gas molecules is not considered. Actually, for example, when the pressure in the slit is 10 Pa, the mean free path is about 0.3 mm, the corresponding Knudsen number is 0.3 (= 0.1 mm slit width/0.3 mm mean free path). This value of the Knudsen number corresponds to the intermediate flow of the gas molecules, where the interaction between the gas molecules exist to some extent. However, because the pressure in the outlet side of the slit is lower and the corresponding Knudsen number is smaller, this region is under molecular flow condition, where the interaction between the gas molecules is negligible. Therefore, the calculated gas distribution results are considered not to be so different from the real one. For the amount of gas injection, the flow of 0.1 Pa l/s is set to the gas inlet surface shown in Fig. 2. The corresponding pressure in the gas reservoir at the gas injection line Pin is roughly 12.5 Pa in this case. The orbits of 10^{12} N_2 molecules were simulated in the calculation. Here the gas

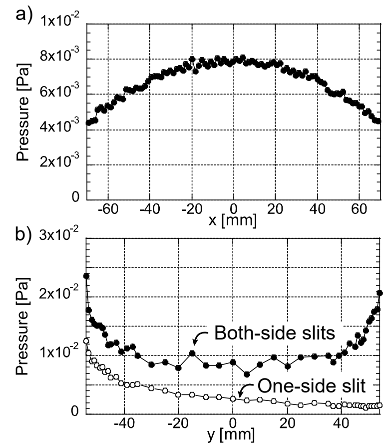

Figure 3: Calculated pressure distribution along a) the x-axis and b) the y-axis.

density n is shown by the pressure P because they have proportional relations as $P = nk_BT$, where k_B and T are the Boltzmann constant and the temperature, respectively.

Figure 3 a) and b) shows the calculated pressure distribution along the x- and y-axis, respectively. Although the pressure becomes lower near the edge of the slit along the x-axis, there is the uniform region around the center of the slit, x = 0. Along the y-axis, the pressure decreases with distance from the slit outlet due to the diffusion of the gas molecules. However, the uniform pressure region exists around the center of the two slits, y = 0. In Fig. 3 b), the pressure distribution in the case of the one-side slit is also shown. The gas density distribution obviously becomes more uniform by the both-side slits than the one-side slit. This is because the gas density, which decreases with distance from the slit due to the diffusion, is compensated by the gas injected from the other side of the slit. The realistic region of the LINAC beam size is |x| ≤ 10 mm and |y| ≤ 10 mm. In this region, the non-uniformity of the gas density distribution is less than the variation from statistics. Figure 4 shows the pressure distributions along the z-axis. at the center and edge points in the typical realistic beam size, |x| ≤ 10 mm and |y| ≤ 10 mm. There is no difference in the pressure distributions, which means that the gas density distribution along the z-axis is also enough uniform in the realistic beam size region.

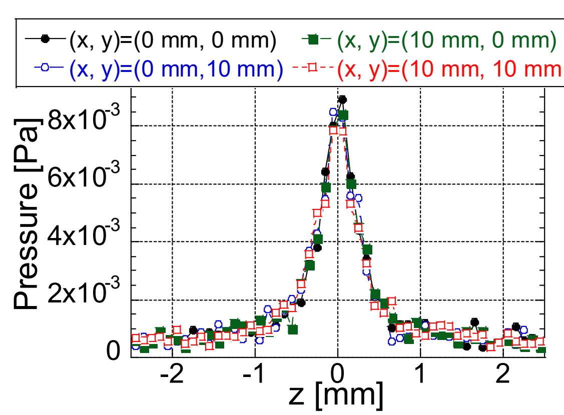

Figure 4: Calculated pressure distribution along the z-axis.

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DEPENDENCE ON THE MCP VOLTAGE AND GAS INJECTION LINE PRESSURE

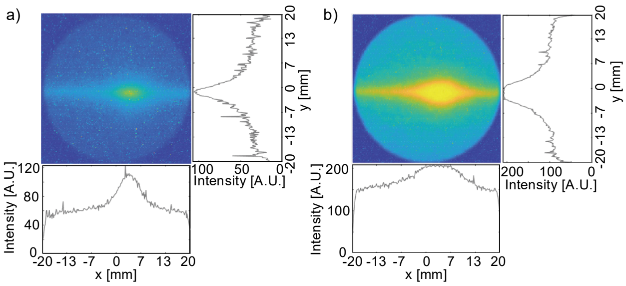

Figure 5: Typical beam profile for the different applied voltages on the MCP input. a) V_{MCP_in}=-1150 V. b) V_{MCP_in}=-1350 V.

Figure 5 shows detected typical beam profiles for the different voltages on the MCP input V_{MCPin}. The MCP output is fixed to the earth potential. The beam energy E and peak current I_{beam} was 400 MeV and 40 mA, respectively. The pressure in the gas injection line P_{in} was set to 1.9 Pa. The peak of the beam profile with high voltage seems to be saturated (Fig. 5 b)). To discuss the V_{MCPin} dependence qualitatively, the horizontal and vertical profiles were fitted by a Gaussian plus linear function

$$f(x) = ae^{-\frac{(x-b)^2}{2c^2}} + dx + e,$$

where a-e are, fitting parameters. The actual beam size along the x-axis has to be corrected by multiplying $\tan\theta$, where θ is the angle of the gas sheet against the beam trajectory, 30º as shown in Fig. 1. However, this time, the angle correction is not considered because the relative tendency is examined.

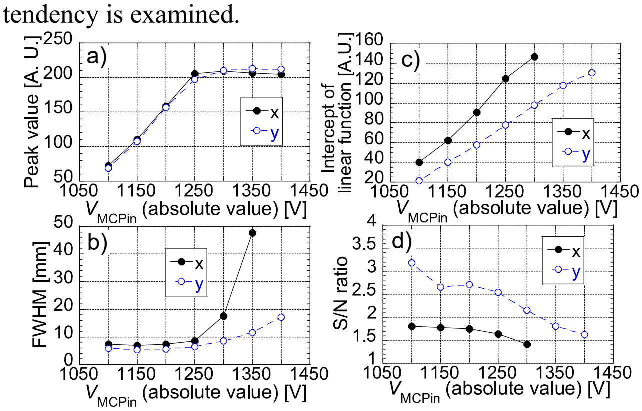

Figure 6: V_{MCPin} dependence of a) peak value of the fitting function, b) FWHM of the Gaussian function and c) intercept of the linear function, and d) S/N ratio.

Figure 6 shows the dependence of the peak value of the function, FWHM of the Gaussian function, an intercept of the linear function e, and the S/N ratio, which is defined as the peak value divided by intercept value. In this condition, the peak current is proportional to the V_{MCPin} value from 1100 to 1250 V in a negative value. The peak value is saturated above 1250 V in negative V_{MCPin} value. Along with the saturation, the FWHM unrealistically increases. Furthermore, the S/N ratio is reduced due to the peak saturation with the increasing V_{MCPin} in addition to the increases of the background noise. In the measurement of the dependence on P_{in}, V_{MCPin} was fixed to -1150 V. To avoid saturation, the measurement was performed in the low P_{in} region as small as possible. Figure 7 shows the dependence of each value on Pin. The peak value and S/N ratio are proportional to the P_{in} and the FWHM does not change. Thus, no saturation of the peak was observed in the low P_{in} region. The peak value would be saturated with a much higher P_{in} range. Thus, for the proper beam profile measurement, the low pressure in the gas injection line is ideal. In addition, the low pressure in the gas injection line also has the advantage of a negligible increase in the beam line pressure due to the small amount of the injected gas.

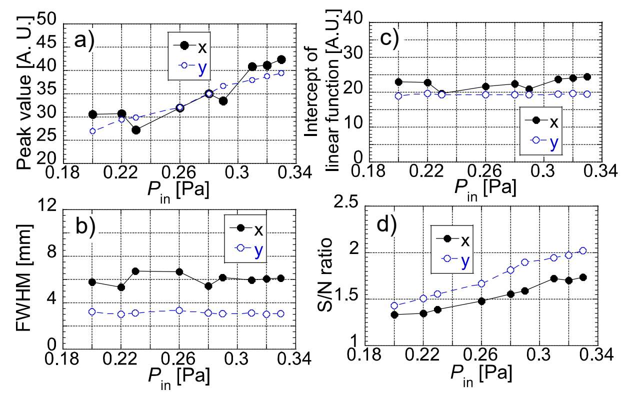

Figure 7: P_{in} dependence of each value of the profile. The meaning of each panel is the same as Fig. 6. Notice P_{in} value is very low, which means the injected gas is very small in this condition.

CONCLUSION

The gas-sheet based beam profile monitor system in the J-PARC LINAC was evaluated. The calculation result showed that the non-uniformity of the gas density distribution was less than the variation from statistics in the realistic beam size. The both-side slits geometry is found to be effective to make the uniform distribution along the y-axis. The system to directly measure the gas density distribution is now under development [5]. At P_{in} was 1.9 Pa, the linear response region was obtained for the absolute V_{MCPin} value less than 1250 V. No saturation of the peak was observed in the low P_{in} range less than 0.35 Pa. It is concluded that for the proper beam profile measurement, the condition with the gas injection line pressure as low as possible in the linear response region to the MCP voltage is ideal.

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